Dob's Linn – the Ordovician–Silurian Boundary Stratotype

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Synopsis

Dob's Linn, north-east of Moffat, southern Scotland, has been designated the Ordovician–Silurian boundary stratotype by the Ordovician–Silurian Boundary Working Group of the I.U.G.S. Commission on Stratigraphy. The boundary is placed at the base of the *P. acuminatus* Zone, marked by the first occurrence of *Akidograptus ascensus* and *Parakidograptus acuminatus*, *s.l.*, 1·6 m above the base of the Birkhill Shale in the Linn Branch section.

The stratigraphical interval covering this boundary consists of richly graptolitic black shale. Occasional metabentonites are also present. The underlying Upper Hartfell Shale is composed predominantly of pale grey-green, non-graptolitic shale and mudstone, with several black graptolitic bands referred to the *Complanatus*, *Anceps* and *Extraordinarius* Bands. The rich faunal assemblage of the *Anceps* Band reduces to only three diplograptid taxa in the *Extraordinarius* Band. This major extinction is recorded at an equivalent horizon by all other graptolitic sequences throughout the globe.

Sediments of the Upper Ordovician to Lower Silurian Moffat Shale Group were probably deposited entirely by distal turbidites in the abyssal depths of the Iapetus Ocean. Northerly-directed subduction subsequently transported the site of shale deposition into a proximal turbidite environment, resulting in a diachronous transition into coarse clastics of the overlying Gala Greywacke Group. Deformation related to subduction also produced imbricate thrusting and raised the area to a prehnite-pumpellyite facies metamorphic grade. Geophysical evidence indicates that the region is underlain by continental basement; this suggests that the Southern Uplands are allochthonous.

Historical introduction

Graptolites were first recorded from Dob's Linn, southern Scotland over one hundred years ago. The earliest publications to include descriptions of the fauna from the Moffat Shales (e.g. Carruthers 1858; Nicholson 1867; Dairon 1869; Hopkinson 1871) paid little or no attention to their stratigraphical importance. Elsewhere during this period, an ever increasing volume of articles on graptolites was being published, including a number which recognized their great potential for both regional and global correlation (Nicholson 1876). These included studies on the Lower Ordovician of northern England (e.g. Nicholson 1870, 1875), South Wales (Hopkinson & Lapworth 1875) and eastern Canada (Hall 1858, 1865; Billings 1865).

In 1864 Charles Lapworth obtained a teaching post connected with the Episcopal Church at Galashiels some 30 km north-east of Dob's Linn (Gibson 1921). He had no previous geological training or experience, but soon developed an interest in the local geology of the Southern Uplands. Harkness (1851) had described the repeated, faulted nature of this area composed of thick greywacke and containing a shale sequence termed the 'Moffat Series'. Otherwise this structurally complex region still defied satisfactory interpretation despite attempts by several other eminent geologists (e.g. Sedgwick 1850).

Lapworth's first publication on the Lower Palaeozoic (1870) concerned the geology of the Galashiels area. During these early years in his geological career, he recorded graptolites both from within the thick greywacke sequence of the Southern Uplands and from the underlying black shales. A summary of Lapworth's early lithostratigraphical division was published in 1872. During the next five years he completed an exercise of detailed geological mapping, logging of sections and bed-by-bed faunal collecting throughout the Moffat area. A selection of new graptolite taxa were figured and discussed briefly in 1876, while similar faunas were also illustrated from equivalent strata in northern Ireland (Lapworth 1877).

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Lapworth's major stratigraphical synthesis 'On the Moffat Series' was published in 1878, where he established beyond doubt the precise, ordered stratigraphical change in graptolite assemblages through the sequence of black and grey shales. With the exception of the Glenkiln Shale (best developed at Glenkiln Burn, south-east of Moffat) and the lowermost portion of the Lower Hartfell Shale (best exposed at Hartfell Spa, north of Moffat), Lapworth used the Main Cliff and Linn Branch sections of Dob's Linn as the standard reference for the Moffat Shale. While working at Dob's Linn, Lapworth stayed at Birkhill Cottage only a few hundred metres above the locality. The uppermost black shale division of the group was named after this cottage.

Lithological sections measured at Dob's Linn, together with graptolite assemblages and biostratigraphical divisions, were figured by Lapworth (1878: figs 27–30) in his major work, where the lithostratigraphical division of the Moffat Shale was also clearly defined. An earlier, less detailed log of the Moffat Shale from Lapworth's notes, covering the Glenkiln Shale to basal Birkhill Shale, is still preserved in Birmingham University, and is here illustrated for comparison (Fig. 1). Note that Lapworth's assignment of the lower part of the Upper Hartfell Shale to the 'Belcraig Shale' (after Beldcraig Burn near Moffat) was apparently never published.

During this research, Lapworth was appointed in 1875 to an Assistant Mastership at Madras College, St Andrews. In 1881 he was elected to the Chair of Geology at the recently established Mason College, Birmingham, which subsequently became the University of Birmingham. In addition to elucidating the structure of the Southern Uplands, Lapworth established the Ordovician System in 1879, solving the embittered feud between the schools of Murchison and Sedgwick (see Bassett 1985). He also made an equally painstaking, detailed stratigraphical study at Girvan on the south-west coast of Scotland (Lapworth 1882). His conclusions regard-

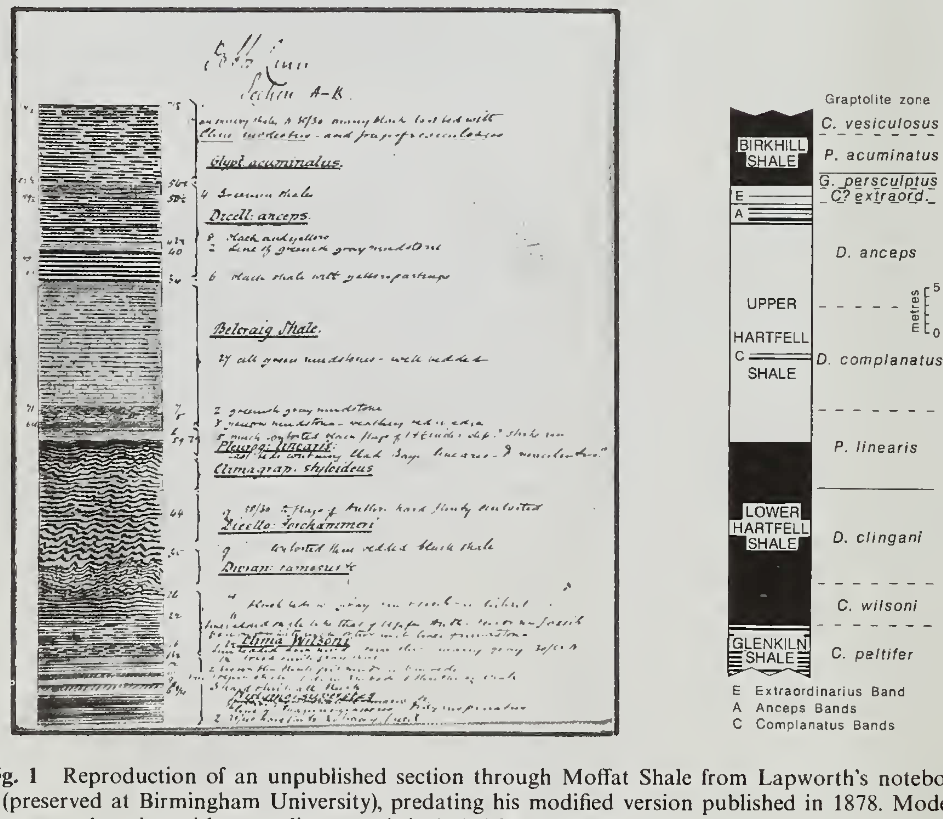

Fig. 1 Reproduction of an unpublished section through Moffat Shale from Lapworth's notebook (preserved at Birmingham University), predating his modified version published in 1878. Modern measured section with graptolite zones is included for comparison.

ing the relationship between the strata at Girvan and those of the Southern Uplands were published in 1889.

The work of Lapworth was drawn upon heavily by Peach & Horne (1899), who also described many confirmatory sections through the Moffat Shale in the Southern Uplands. With the exception of one taxonomic paper published by Lapworth in 1880, most of his new graptolite taxa were first described fully by Elles & Wood (1901–18), whose work he supervised throughout its production. Following this major publication, little taxonomic or stratigraphical work was attempted at Dob's Linn for half a century. One notable exception was an article by Davies (1929), who included Dob's Linn in his detailed study of late Ordovician and early Silurian graptolites.

A series of recent biostratigraphical and taxonomic papers was initiated by Packham (1962), who described the evolution of *Glyptograptus tamariscus* and related diplograptids from the Birkhill Shale of Dob's Linn and from the Lower Silurian of the Rheidol Gorge, mid Wales. Toghill (1968) discussed the evolution of the earliest monograptids and formally established the presence of the *G. persculptus* Zone at Dob's Linn. He also gave a biostratigraphical summary of the entire Birkhill Shale with listings of the zonal assemblages (1968a), but none of the fauna was described or illustrated.

Toghill (1970) subsequently published a revision of graptolites from the Upper Hartfell Shale and top Lower Hartfell Shale. Brief taxonomic descriptions and illustrations were included; this paper added little in terms of refinement to Lapworth's biostratigraphical divisions, but was important in demonstrating the presence of previously unrecorded graptolite species. Cocks *et al.* (1970) used this data to make a premature proposal of Dob's Linn as the Ordovician–Silurian boundary stratotype, where they placed the boundary at the base of the Birkhill Shale (= 'base' of *G. persculptus* Zone). Rickards (1979) added the record of the *C.? extraordinarius* Zone, based on the discovery by Ingham (1979) of a black, graptolitic shale band midway between the top *Anceps* Band of the Upper Hartfell Shale and the basal Birkhill Shale.

A geological locality map of Dob's Linn was given by Toghill (1968*a*), but most geologists visiting the locality were still guided by the remarkably detailed geological map published by Lapworth in 1878. Following several years' critical work using aerial and ground photographic overlays and modern structural synthesis, Ingham (1979) published a totally revised geological map of Dob's Linn. During the course of this research, Ingham found that several of Toghill's measured sections through the Upper Hartfell and lowermost Birkhill Shales were disrupted structurally and measurements were consequently revised. Ingham's recognition of unbroken sections and several new graptolitic bands in the Upper Hartfell Shale (upper *Complanatus* Band, *Anceps* Band A and the *Extraordinarius* Band), permitted critical faunal recollection of the Moffat Shale. This task was begun by the present author in 1978, leading to a series of taxonomic and biostratigraphical papers covering the top 8 m of the Lower Hartfell Shale (Williams 1982*a*), the *Complanatus* Bands (Williams & Ingham, in prep.), the *Anceps* Bands (Williams 1982), the *Extraordinarius* Band and the basal 2 m of Birkhill Shale (Williams 1983).

These papers confirmed Lapworth's original faith in graptolites as a critical biostratigraphical tool and gave more precise definitions of the zonal boundaries. Of particular importance is the revised, unambiguous definition of the boundary between the *G. persculptus* and *P. acuminatus* Zones, the horizon now defined as the Ordovician–Silurian boundary.

Regional setting, stratigraphy and depositional environment

The geology of the Southern Uplands is dominated by a thick package of monotonous, sparsely graptolitic greywackes, belonging to the Gala Greywacke Group. This is of unequivocal turbidite origin. The underlying Moffat Shale Group is exposed as a series of elongate, narrow, east-west inliers which Lapworth (1878) and Peach & Horne (1899) considered to represent tight, isoclinal anticlines. It is now considered (Webb 1983) that these structures were formed through progressive shearing of early folds. The appearance of simple, reverse faulting postulated by Craig & Walton (1959), Leggett *et al.* (1979), Eales (1979) and other recent workers is due to almost complete removal of the shorter, south-eastern limbs.

An overall younging and progressive lateral change in lithologies from north to south was recognized in the Southern Uplands by Peach & Horne (1899). They divided the regions into three tracts, namely the Northern, Central and Southern Belts. The rock types and age ranges of strata characterizing each belt have since been summarized in detail by Leggett *et al.* (1979), who considered division into ten discrete sequences to be more appropriate. In the most northerly sequences red cherts, siliceous mudstones and pillow basalts of Arenig to Llandeilo age are overlain by Llandeilo–Caradoc greywackes. This succession passes southwards to Llandeilo–Llandovery cherts and black shales overlain by Llandovery greywackes. The diachronous base of the greywackes youngs progressively to the south, with consequently extended black shale deposition. The most southerly sequences of the Southern Uplands are composed entirely of Wenlock greywackes.

Both the structural pattern of the Moffat Shale outcrops and the diachronous base of the greywackes were explained in a model proposed by Mitchell & McKerrow (1975) and expanded by McKerrow *et al.* (1977) and Leggett *et al.* (1979). These authors considered the Southern Uplands to have formed as an accretionary prism over a northerly dipping subduction zone on the northern margin of the Iapetus Ocean. The prehnite-pumpellyite metamorphic facies could have resulted from burial and tectonic processes during such accretion (Oliver *et al.* 1984). Geophysical studies (Powell 1971; Hall *et al.* 1983), however, indicate crystalline, continental material underlying the area, rather than the oceanic basement required for this model. Bluck (1984) discussed this apparently contradictory evidence; he concluded that the Southern Uplands are probably allochthonous. More recently, Needham & Knipe (1986) reiterated the accretionary prism model, but this was considered inadequate by Murphy & Hutton (1986), who concluded that subduction at both Iapetus margins was complete by late Ordovician times and that the Silurian turbidites were deposited in a successor basin.

The Moffat Shale Group is divided into four formations: the Glenkiln Shale, Lower Hartfell Shale, Upper Hartfell Shale and Birkhill Shale (Lapworth 1878). The Glenkiln Shale is composed of an unknown thickness of pale grey and black, heavily silicified argillites. At Dob's Linn the formation is poorly exposed as a series of disconnected, fault-bounded slivers. It is generally unfossiliferous and due to heavy shattering of the competent, siliceous component, even black lithologies rarely yield identifiable graptolites. Useful comparative sections are exposed at the type section of Glenkiln Burn and at several other inliers in the Moffat area (Lapworth 1878; Peach & Horne 1899).

The Glenkiln Shale apparently passes gradationally into the almost continuously black Lower Hartfell Shale, which yields a more abundant graptolite fauna and is over 20 m thick. The lower half of the formation remains highly siliceous; the proportion of chert to black shale decreases upwards throughout the unit, black shale becoming predominant in the upper 5 m.

The overlying Upper Hartfell Shale is composed mostly of monotonous, non-graptolitic, pale grey/green shales and mudstones 28 m thick (Figs 1, 2). Its lower boundary is marked by a transitional 3 cm interval of alternating pale grey and black laminae. Three groups of graptolitic, black shale bands occur within the formation, named the *Complanatus*, *Anceps* and *Extraordinarius* Bands (Ingham 1974, 1979) after their diagnostic zonal assemblages (Fig. 1). Other atypical lithologies include nodular limestones and one detrital limestone. The latter horizon is a very pale grey, coarse-grained limestone 6·5 cm thick, lying 1·5 m below the lower *Complanatus* Band in the banks of the Linn Branch stream. Unfortunately it has been totally recrystallized and affected by strain-induced pressure solution, but it was presumably of detrital origin.

One medium grey nodular limestone, 4 cm thick and lying 2 m above the base of the Upper Hartfell on the North Cliff section, displays uncompacted bioturbation with horizontal to subvertical simple burrows 1–2 mm in diameter. Other nodular horizons present in the Linn Branch section include that known to yield a blind, dalmanitid trilobite 0·1 m below the *Extraordinarius* Band (Ingham 1979) and a second, apparently unfossiliferous bed 0·25 m below the base of the Birkhill Shale. Three of these four limestones were not known prior to recent recollecting for conodont samples (Barnes & Williams, this volume) and other similar horizons in the Upper Hartfell Shale probably still await discovery.

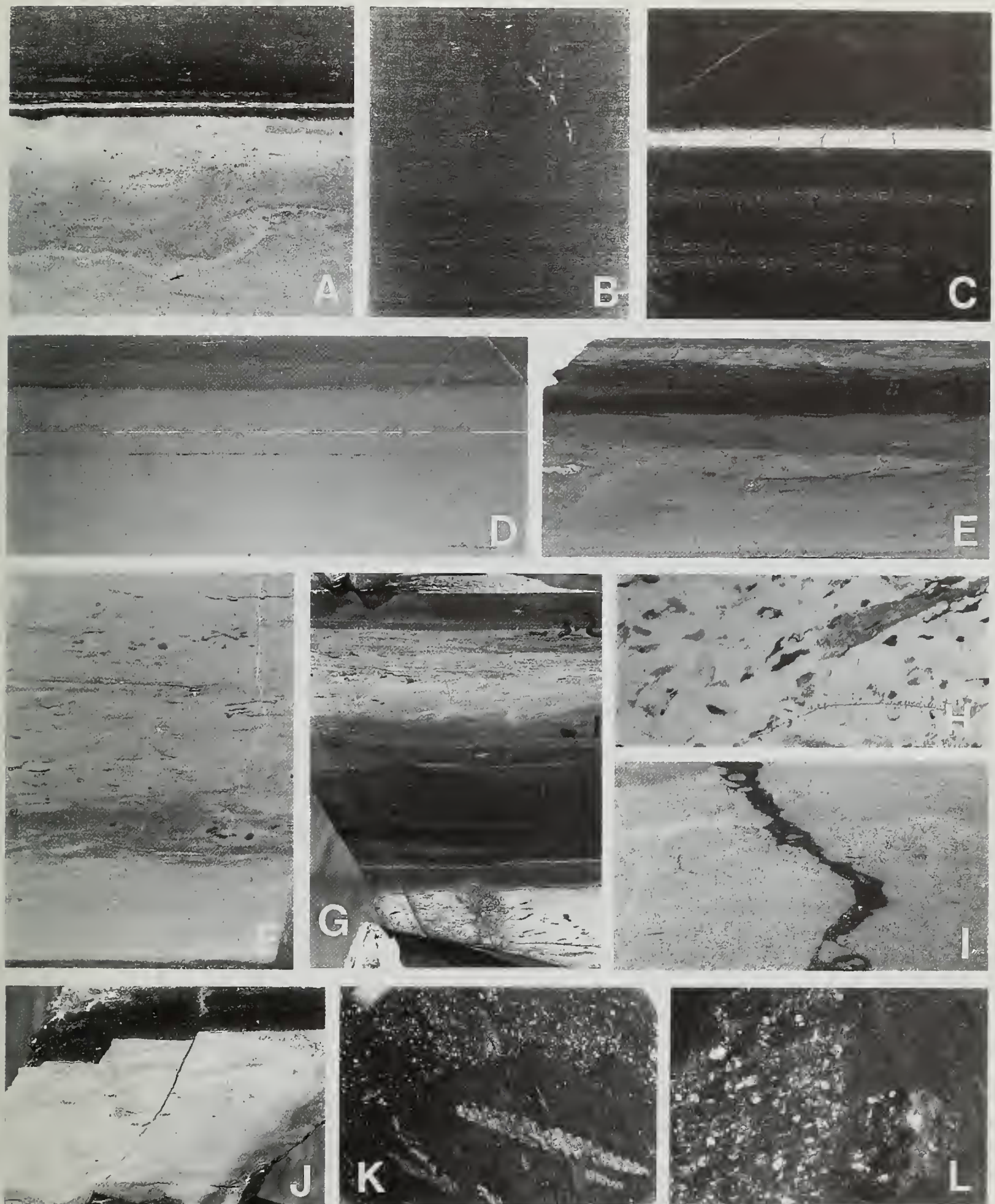

Fig. 2 Sectioned slabs and bedding surfaces from the Moffat Shale at Dob's Linn (all × 2). A. Lower boundary of *Anceps* Band C. B. Typical uniformly laminated black shale, lower Birkhill Shale. C. Black shale, thin metabentonite and micaceous horizons from *Anceps* Band D (note grading shown by metabentonite). D. Uniform pale grey Upper Hartfell Shale lithology, *Anceps* Bands. E. Irregular laminae and compacted bioturbation, base of lower *Complanatus* Band. F. Bioturbation above upper *Complanatus* Band. G. Irregular laminae, compacted bioturbation and low-angle synsedimentary faulting from reversal in Birkhill Shale 0·5 m above base. H. Bedding plane section from base of slab shown in Fig. 2G. I. Black shale injection through pale mudstone, *Anceps* Bands. J. High-angle, post-compactional microfaulting, *Anceps* Band D. K, L. Bedding surfaces with coarse mica flakes, *Anceps* Band D.

The 43 m of Birkhill Shale is composed of black, continuously graptolitic shale in the lower part, with the exception of a temporary reversal to an 'Upper Hartfell' type lithology 0·46–0·56 m above its base. The shales become progressively siltier, less fissile and paler towards the top of the formation, culminating in a transition to coarse turbidites of the overlying Gala Greywacke Group.

The precise depositional environment of the Moffat Shale Group is still uncertain. Lapworth (1897) envisaged black shale formation in a partially restricted 'Sargasso Sea' setting. Later Walton (1963) considered the Moffat Shale to have been deposited on a regional high in a deep ocean environment, explaining the lack of turbidites which are found elsewhere as lateral equivalents and overlying the group.

With the recognition of the Lower Palaeozoic Iapetus Ocean in recent years, it has become evident that the Moffat Shale was deposited within a wide, open ocean of complex history. This suffered continued narrowing throughout the Upper Ordovician and Silurian due apparently to subduction on both northern and southern margins (Moseley 1978, Bluck 1984). The significance of sedimentary features such as postulated winnowing of graptolities, lithological colour alternation, soft-sediment deformation and presence of limited bioturbation (Fig. 2) was discussed by Williams & Rickards (1984). Further observations have emphasized the variation in contacts between pale and black lithologies, from sharp and laminar (Fig. 2A) to gradational and irregular (Figs 2E–G). They have also confirmed the presence of coarse, silty laminae with biotite flakes up to 1 mm diameter, particularly within the *Anceps* Bands of the Upper Hartfell Shale (Figs 2K–L). These strongly suggest a hemipelagic, distal turbidite origin for the sediments, in contradiction to Dewey (1971), Leggett (1980) and Leggett *et al.* (1979), who considered the shale to be of oceanic, truly pelagic origin formed during periods of high eustatic sea level stands. Several black shale sequences elsewhere are known to have been deposited as distal turbidites, including beds of the Burgess Shale of British Columbia (Piper 1972) and of the Cow Head Group, western Newfoundland (Coniglio 1985). It was therefore evident that during Lower Palaeozoic times black shales could form within an unrestricted oceanic setting lacking any degree of restriction, unlike those deposited during Mesozoic and Recent times (e.g. Jenkyns 1978; Stow & Piper 1984).

The presence of metabentonites throughout much of the Moffat Shale indicates sporadic acidic volcanism. Most of these are only laminae or thin beds (Fig. 2C), but they occasionally reach over 5 cm thick. Their lateral impersistence was noted by Williams & Rickards (1984), who suggested variable deposition due to a gently undulating sea floor. It seems likely that the metabentonites were transported by a turbidite mechanism in a similar fashion to the remaining lithologies; they would not, therefore, have significance in terms of proximity to volcanic activity. The single coarse-grained limestone below the lower *Complanatus* Band was probably also deposited by a powerful, carbonate-rich, turbidite flow. Such carbonate detritus was probably derived from a northerly source, such as the sites of fore-arc, shelf and slope deposition at Girvan (Bluck 1984).

No critical sedimentological studies have been carried out on the Moffat Shale at Dob's Linn. With recent advances in both understanding of depositional mechanisms in deep-water, hemipelagic sedimentation (Stow & Piper 1984; Coniglio 1985) and development of new techniques to assist the study of fine-grained sediments, a detailed review of argillites at Dob's Linn and at comparitive sections is now warranted.

Late Ordovician and Early Silurian graptolite biostratigraphy

The following account is based on detailed logging through a trench constructed on the north valley side of the Linn Branch (Figs 3, 4), excepting that of the Lower Hartfell Shale (from the North Cliff trench, Fig. 3) and lower part of the Upper Hartfell Shale, including the *Complanatus* Bands (Linn Branch stream bed).

The uppermost 5 m of the continuously black Lower Hartfell Shale is encompassed within the *Pleurograptus linearis* Zone (Williams 1982*a*). Following this level, 9 m of unfossiliferous grey shale and mudstone belonging to the Upper Hartfell Shale is present before the black,

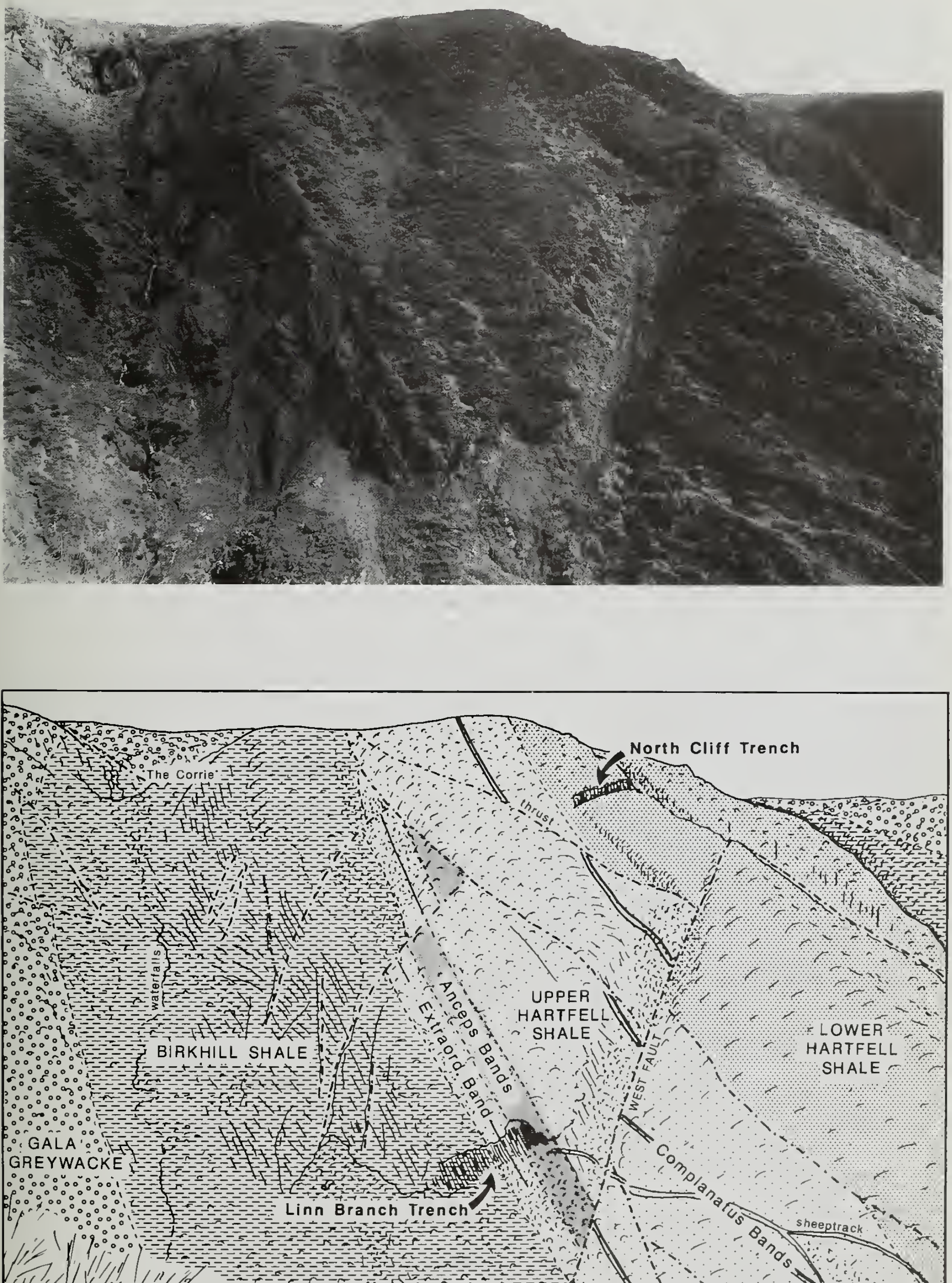

Fig. 3 Photograph showing northern side of Linn Branch gorge, indicating key collecting localities. Interpretation of geology and structure adapted after Ingham (1974: fig. 25).

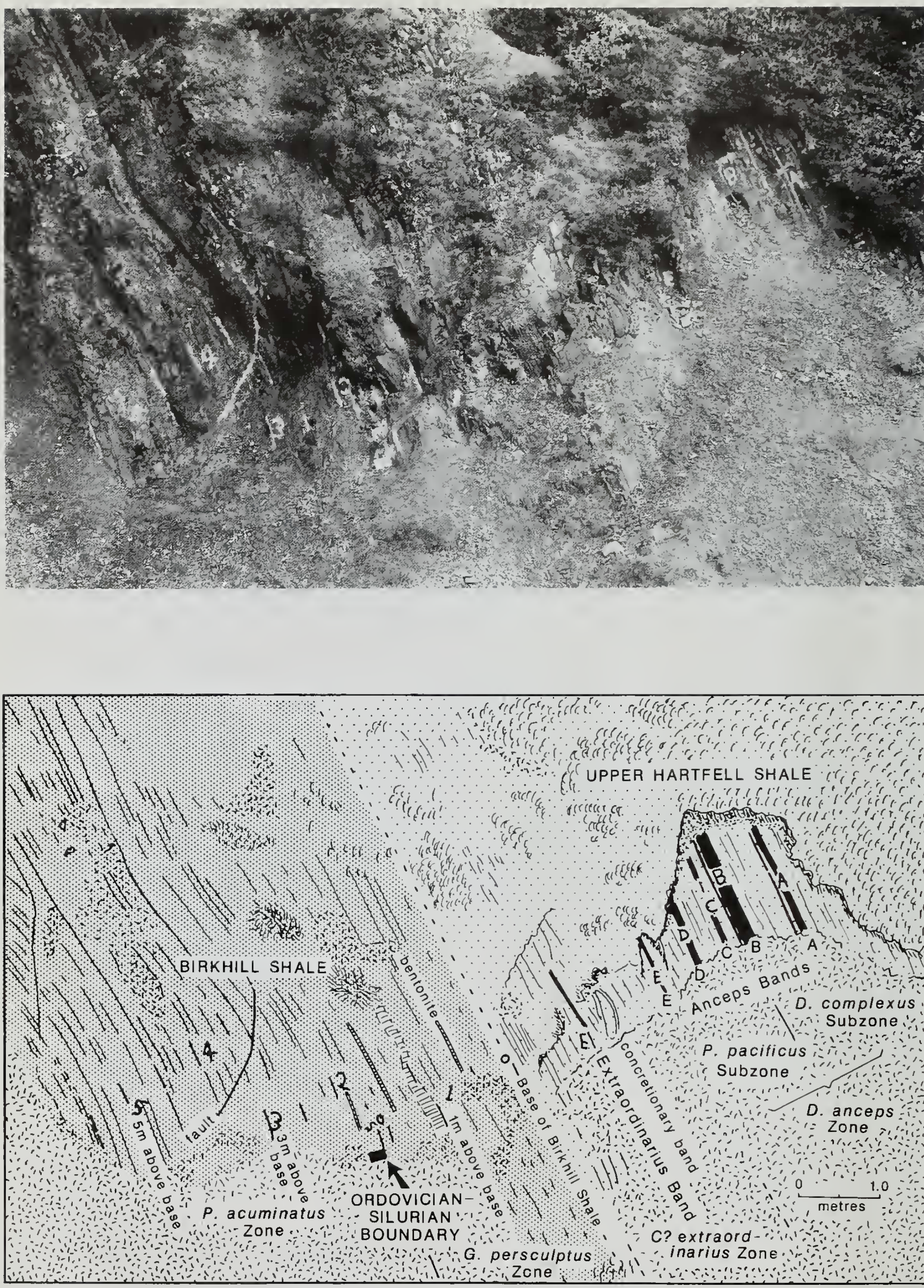

Fig. 4 Photograph of Linn Branch trench with interpretation, photographed from same position as Fig. 2. Notebook lies on position of Ordovician–Silurian boundary.

graptolitic *Complanatus* Bands are reached. Lapworth (1878: 316; fig. 28) originally recorded '*Dicellograptus forchhammeri*, *Climacograptus scalaris?* and *Diplograptus truncatus*'. These specimens were subsequently recognized as new taxa, described by Lapworth (1880) and Elles & Wood (1901–18) as *Dicellograptus complanatus*, *Climacograptus scalaris miserabilis* and *Orthograptus truncatus socialis*. Davies (1929: 18) relocated the graptolite horizon, as did Toghill (1970). Ingham (1974) proved the existence of a second narrow, black seam about 0·4 m above the 4 cm thick, previously recorded band. Williams (1987) records *D. complanatus* Lapworth, *D. minor* Toghill, *C. miserabilis* Elles & Wood, *C. tubuliferus* Lapworth and *O. socialis* (Lapworth) from the lower band. The upper band yields *D. complanatus* and rare specimens of *Orthoretiograptus pulcherrimus* (Keble & Harris). Williams & Lockley (1983) described well preserved specimens of an inarticulate brachiopod, both from within and directly above the upper band, which were assigned to a new genus and species *Barbatulella lacunosa*. Rare, usually fragmented specimens of this brachiopod also occur at several grey mudstone horizons within the following *Anceps* Bands.

The *Anceps* Bands are separated from the *Complanatus* Bands by 13 m of grey barren shale and mudstone. They comprise a series of alternating black and grey shales with common metabentonites, covering an interval which ranges in thickness from 1·6 m on the Main Cliff, to 2·0 m in the Linn Branch trench and 4·5 m in the Long Burn section. The last of these localities is separated from the former two by the Main Fault, and may have been deposited at some distance apart. Other lateral variation in thickness was probably due to deposition on an irregular sea floor and synsedimentary erosion as discussed by Williams & Rickards (1984).

Lapworth (1878: 253, 317) erected the *Dicellograptus anceps* Zone in his major publication on the Moffat Shale, owing to the distinctive nature of the faunal assemblage in the black *Anceps* Bands. Toghill (1970: 6; fig. 1) recorded four black shales; Ingham (1974) however established the presence of five bands or groups of bands, now referred to Bands A to E. The rich, diverse fauna contained within these black shales (Fig. 5) allowed Williams (1982) to divide the zone into the *Dicellograptus complexus* and *Paraorthograptus pacificus* Subzones. In addition to those species' ranges shown on the range chart, rare specimens of *Climacograptus hastatus* Hall and *Glyptograptus posterus* Koren & Tsai have been found in the *D. complexus* and *P. pacificus* Subzones respectively. These taxa confirm correlation with the Australian and Chinese graptolite zonal schemes.

Ingham (1979) was first to discover the *Extraordinarius* Band 0·96 m above *Anceps* Band E. This narrow, dark brown shale contains a sparse graptolite assemblage, identified by Rickards (1979) and Williams (1983) as *Climacograptus? extraordinarius* (Sobolevskaya), *Climacograptus* sp. indet. and *Glyptograptus?* sp. indet. The grey strata separating the *Extraordinarius* Band from *Anceps* Band E is unfossiliferous, with the exception of a nodular limestone 0·1 m below the *Extraordinarius* Bands which yields rare fragmentary specimens of a blind dalmanitid trilobite (Ingham 1979).

The lower boundary of the Birkhill Shale lies 1·17 m above the *Extraordinarius* Band. Following a basal, unfossiliferous black shale interval 0·15 m thick, an abundant but poorly diverse graptolite fauna is present, including *Climacograptus normalis* Lapworth, *C. miserabilis* Elles & Wood and *Glyptograptus?* '*venustus* cf. *venustus*' (Legrand). A temporary reversal to alternating grey/green and black shales occurs at 0·46 to 0·56 m above the base. This is followed by black shales yielding a better preserved, more diverse assemblage with the addition of *Glyptograptus* cf. *persculptus* (Salter) and *Glyptograptus? avitus* Davies. Lapworth (1878) referred the basal Birkhill Shale to the *P. acuminatus* Zone. The *G. persculptus* Zone was first separated as a biostratigraphical unit underlying the *P. acuminatus* Zone in central Wales by Jones (1909, 1921), where he also considered it to be lithologically different. Davies (1929) ratified the presence of two distinct zones and recognized the interval equivalent to the *G. persculptus* Zone in both northern England and southern Scotland. It appears that he referred three 'horizons' below the first occurrence of *Parakidograptus acuminatus* (Nicholson) and *Akidograptus ascensus* Davies to the *G. persculptus* Zone at Dob's Linn (1929: 22; fig. 32), but this is not stated unequivocally in the text. Adoption of the *G. persculptus* Zone as a formally defined, distinct biostratigraphic unit at Dob's Linn was not realized prior to Toghill's revision

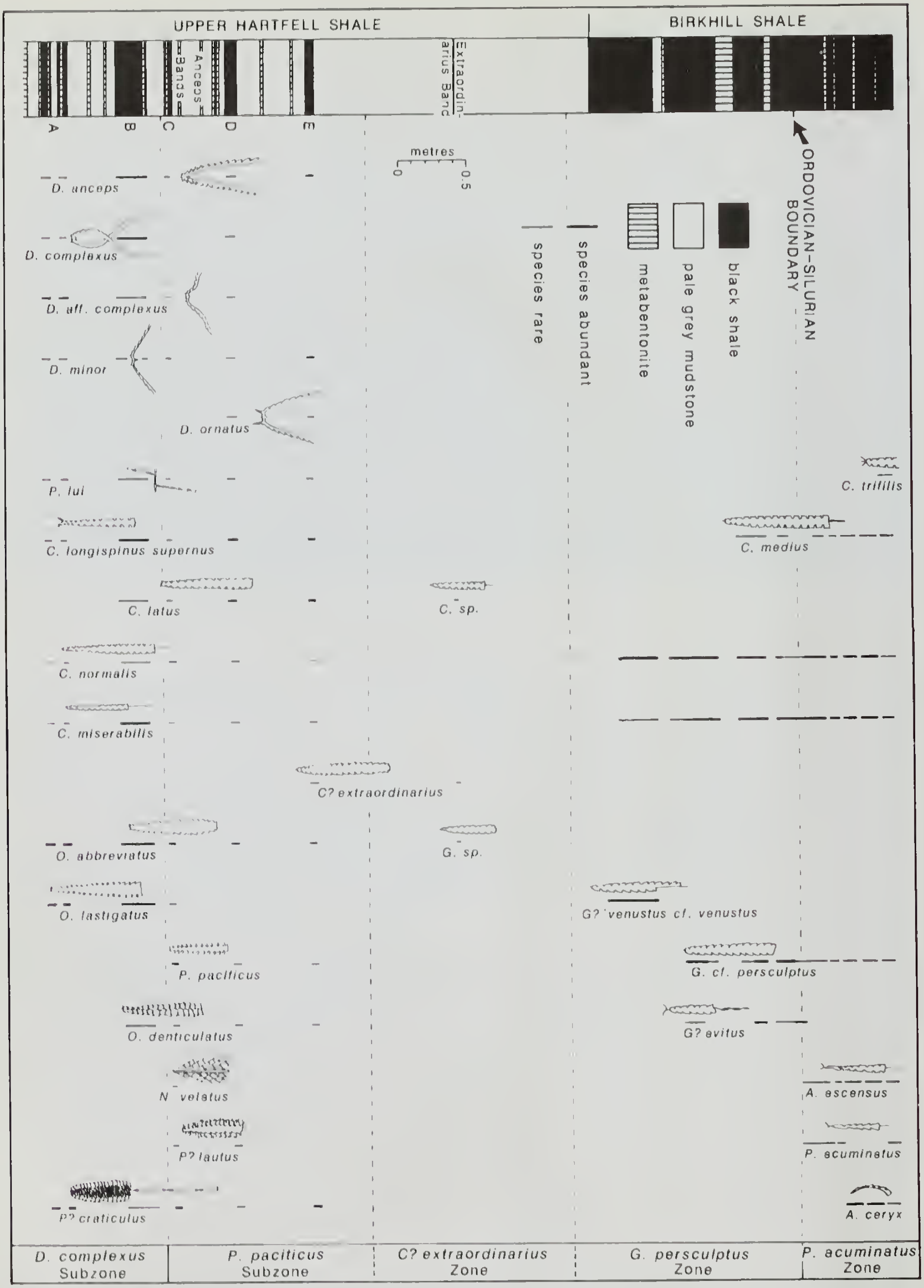

Fig. 5 Detail of sediments and graptolite ranges for the top Upper Hartfell Shale and basal Birkhill Shale.

of the Birkhill Shale in 1968. Rickards (1970) and Hutt (1974) also used this zone as the basal biostratigraphic division of the Lower Silurian Skelgill Formation in northern England.

The base of the *P. acuminatus* Zone is marked by the first appearance of *Akidograptus ascensus* Davies and *Paraorthograptus acuminatus* (Nicholson) *s.l.* at 1·6 m above the base of the Birkhill Shale (Fig. 5). It is this level which has now been adopted as the defined Ordovician–Silurian boundary (Cocks 1985), marked by the first occurrence of *A. ascensus*. Most previous publications (e.g. Toghill 1968*a*; Cocks *et al.* 1970) have taken the base of the Birkhill Shale as marking the Ordovician–Silurian boundary. This interval covers a change from grey to black shale, is unfossiliferous and clearly unsuited as a zonal boundary, let alone for an international system boundary stratotype. Similar barren intervals seem to occur at this level in every other graptolitic succession in the world; they are probably related to eustatic sea level changes induced by late Ordovician glaciation in the southern hemisphere (see Rong 1984).

In addition to the problem of barren intervals, faunal changes accompanying the transition between the *G. persculptus* and *C.? extraordinarius* Zones are poorly understood. Few graptolite taxa are present, following the mass extinction at the *D. anceps–C.? extraordinarius* zonal boundary. Elles (1922, 1925) referred the basal interval of the Birkhill Shale to the 'Zone of *Glyptograptus persculptus* and *Cephalograptus acuminatus*'. In the earlier of these publications (1922: 195) she suggested that this lowest Llandovery zone should perhaps be assigned to the Ordovician owing to the lack of monograptids. It is interesting to note that this proposal has now been partially adopted.

Atavograptus ceryx (Rickards & Hutt) occurs 1·9 to 2·3 m above the base of the Birkhill Shale. Recent recollecting indicates that it is probably restricted to such a level low in the *P. acuminatus* Zone at Dob's Linn. *A. ceryx* was first recorded from strata referred to the *G. persculptus* Zone in the English Lake District (Rickards & Hutt 1970), but was later found in the basal *P. acuminatus* Zone of that area (Hutt 1975), in association with *A. ascensus*.

Monograptus cyphus praematurus Toghill and *Atavograptus atavus* (Jones) are the next monograptids found at Dob's Linn, marking the boundary between the *P. acuminatus* and *Cystograptus vesiculosus* Zones (Toghill 1968*a*). Lapworth (1882: 624) recorded an assemblage of '*Climacograptus scalaris*, *Dimorphograptus acuminatus* and *?Monograptus tenuis*' from a section through the Lower Silurian at Girvan, south-west Scotland. Jones (1921: 155) remarked that such an assemblage seemed anomalous for the *P. acuminatus* Zone; it may, however, prove that the monograptid was *A. ceryx* and that the interval was equivalent to the early *P. acuminatus* Zone of Dob's Linn and northern England. Relocation and recollection of Lapworth's horizon could clearly prove significant as a comparative basal Silurian section.

Future research

Dob's Linn has now been adopted as Ordovician–Silurian boundary stratotype, the boundary being set at the base of the *P. acuminatus* Zone 1·6 m above the base of the Birkhill Shale in the Linn Branch trench (Figs 4, 5). This renders necessary ratification and expansion of Williams' (1983) study of the interval. Other outstanding research still required includes:

1. Detailed study of the basal Birkhill Shale at remaining sections of Dob's Linn, and at other comparative localities in the Central Belt of the Southern Uplands.
2. Biostratigraphical and taxonomic revision of the Glenkiln Shale, the lower part of the Lower Hartfell Shale and remainder of the Birkhill Shale, employing continuous, bed-by-bed collecting techniques.
3. Critical sedimentological logging and study of the Moffat Shale at Dob's Linn, with subsequent integration of faunal data, in order to provide a clearer understanding of original depositional setting.

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